4.3 Minimum Spanning Trees

- introduction
- cut property
- edge-weighted graph API
- Kruskal’s algorithm
- Prim’s algorithm
- context
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**Spanning tree**

**Def.** A spanning tree of $G$ is a subgraph $T$ that is:

- A tree: connected and acyclic.
- Spanning: includes all of the vertices.

![Graph G and spanning tree T](image)
**Spanning tree**

**Def.** A *spanning tree* of $G$ is a subgraph $T$ that is:

- A *tree*: connected and acyclic.
- *Spanning*: includes all of the vertices.

![Diagram of a spanning tree](image)
**Spanning tree**

**Def.** A **spanning tree** of $G$ is a subgraph $T$ that is:
- A tree: connected and acyclic.
- Spanning: includes all of the vertices.

(not a tree (cyclic))
**Spanning tree**

**Def.** A **spanning tree** of $G$ is a subgraph $T$ that is:

- A tree: connected and acyclic.
- Spanning: includes all of the vertices.

![Diagram of spanning tree](image-url)
Minimum spanning tree problem

Input. Connected, undirected graph $G$ with positive edge weights.
Minimum spanning tree problem

Input. Connected, undirected graph $G$ with positive edge weights.
Output. A spanning tree of minimum weight.

Brute force. Try all spanning trees?
Minimum spanning trees: quiz 1

Let $T$ be a spanning tree of a connected graph $G$ with $V$ vertices. Which of the following statements are true?

A. $T$ contains exactly $V - 1$ edges.
B. Removing any edge from $T$ disconnects it.
C. Adding any edge to $T$ creates a cycle.
D. All of the above.
Image processing

MST dithering

http://www.flickr.com/photos/quasimondo/2695389651
Models of nature

MST of random graph

http://algo.inria.fr/brouin/gallery.html
MST describes arrangement of nuclei in the epithelium for cancer research

http://www.bccrc.ca/ci/ta01_archlevel.html
Slime mold grows network just like Tokyo rail system

Rules for Biologically Inspired Adaptive Network Design

Atushi Tero,1,2 Seiji Takagi,3 Tetsu Saigusa,3 Kentaro Ito,3 Dan P. Bebber,4 Mark D. Fricker,4 Kenji Yumiki,5 Ryo Kobayashi,5,6 Toshiyuki Nakagaki5,6*

https://www.youtube.com/watch?v=GwKuFREOgmo
Applications

MST is fundamental problem with diverse applications.

- Dithering.
- Cluster analysis.
- Max bottleneck paths.
- Real-time face verification.
- LDPC codes for error correction.
- Image registration with Renyi entropy.
- Find road networks in satellite and aerial imagery.
- Reducing data storage in sequencing amino acids in a protein.
- Model locality of particle interactions in turbulent fluid flows.
- Autoconfig protocol for Ethernet bridging to avoid cycles in a network.
- Network design (communication, electrical, hydraulic, computer, road).
- Approximation algorithms for **NP**-hard problems (e.g., TSP, Steiner tree).

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Simplifying assumptions

For simplicity, we assume:

- The graph is connected. \( \Rightarrow \) MST exists.
- The edge weights are distinct. \( \Rightarrow \) MST is unique.  

see Exercise 4.3.3

**Note.** Algorithms still work correctly even if duplicate edge weights.
**Cut property**

**Def.** A cut in a graph is a partition of its vertices into two (nonempty) sets.  
**Def.** A crossing edge connects a vertex in one set with a vertex in the other.

**Cut property.** Given any cut, the crossing edge of min weight is in the MST.
Which is the min weight edge crossing the cut \{2, 3, 5, 6\}?

A. 0–7 (0.16)
B. 2–3 (0.17)
C. 0–2 (0.26)
D. 5–7 (0.28)
Def. A cut is a partition of a graph’s vertices into two (nonempty) sets.

Def. A crossing edge connects two vertices in different sets.

Cut property. Given any cut, the min-weight crossing edge $e$ is in the MST.

Pf. Suppose $e$ is not in the MST.

- Adding $e$ to the MST creates a cycle.
- Some other edge $f$ in cycle must be a crossing edge.
- Removing $f$ and adding $e$ is also a spanning tree.
- Since weight of $e$ is less than the weight of $f$, that spanning tree has lower weight.
- Contradiction. □
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Weighted edge API

Edge abstraction needed for weighted edges.

```java
public class Edge implements Comparable<Edge>
{
    Edge(int v, int w, double weight) {
        // create a weighted edge v-w
    }

    int either() {
        // either endpoint
    }

    int other(int v) {
        // the endpoint that's not v
    }

    int compareTo(Edge that) {
        // compare this edge to that edge
    }

    double weight() {
        // the weight
    }

    String toString() {
        // string representation
    }
}
```

Idiom for processing an edge e: `int v = e.either(), w = e.other(v);`
Weighted edge: Java implementation

```java
public class Edge implements Comparable<Edge> {
    private final int v, w;
    private final double weight;

    public Edge(int v, int w, double weight) {
        this.v = v;
        this.w = w;
        this.weight = weight;
    }

    public int either() {
        return v;
    }

    public int other(int vertex) {
        if (vertex == v) return w;
        else return v;
    }

    public int compareTo(Edge that) {
        if (this.weight < that.weight) return -1;
        else if (this.weight > that.weight) return +1;
        else return 0;
    }
}
```
## Edge-weighted graph API

<table>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>public class <code>EdgeWeightedGraph</code></td>
<td></td>
</tr>
<tr>
<td><code>EdgeWeightedGraph(int V)</code></td>
<td>create an empty graph with V vertices</td>
</tr>
<tr>
<td><code>EdgeWeightedGraph(In in)</code></td>
<td>create a graph from input stream</td>
</tr>
<tr>
<td><code>void addEdge(Edge e)</code></td>
<td>add weighted edge e to this graph</td>
</tr>
<tr>
<td><code>Iterable&lt;Edge&gt; adj(int v)</code></td>
<td>edges incident to v</td>
</tr>
<tr>
<td><code>Iterable&lt;Edge&gt; edges()</code></td>
<td>all edges in this graph</td>
</tr>
<tr>
<td><code>int V()</code></td>
<td>number of vertices</td>
</tr>
<tr>
<td><code>int E()</code></td>
<td>number of edges</td>
</tr>
<tr>
<td><code>String toString()</code></td>
<td>string representation</td>
</tr>
</tbody>
</table>

**Conventions.** Allow self-loops and parallel edges.
Edge-weighted graph: adjacency-lists representation

Maintain vertex-indexed array of Edge lists.
Edge-weighted graph: adjacency-lists implementation

```java
public class EdgeWeightedGraph {
    private final int V;
    private final Bag<Edge>[] adj;

    public EdgeWeightedGraph(int V) {
        this.V = V;
        adj = (Bag<Edge>[]) new Bag[V];
        for (int v = 0; v < V; v++)
            adj[v] = new Bag<Edge>();
    }

    public void addEdge(Edge e) {
        int v = e.either(), w = e.other(v);
        adj[v].add(e);
        adj[w].add(e);
    }

    public Iterable<Edge> adj(int v) {
        return adj[v];
    }
}
```

- same as Graph, but adjacency lists of Edges instead of integers
- constructor
- add edge to both adjacency lists
Minimum spanning tree API

Q. How to represent the MST?

```java
public class MST
{
    MST(EdgeWeightedGraph G) constructor
    Iterable<Edge> edges() edges in MST
    double weight() weight of MST
}
```
4.3 Minimum Spanning Trees

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- context
Kruskal’s algorithm demo

Consider edges in ascending order of weight.
- Add next edge to tree $T$ unless doing so would create a cycle.

graph edges sorted by weight

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0-7</td>
<td>0.16</td>
</tr>
<tr>
<td>2-3</td>
<td>0.17</td>
</tr>
<tr>
<td>1-7</td>
<td>0.19</td>
</tr>
<tr>
<td>0-2</td>
<td>0.26</td>
</tr>
<tr>
<td>5-7</td>
<td>0.28</td>
</tr>
<tr>
<td>1-3</td>
<td>0.29</td>
</tr>
<tr>
<td>1-5</td>
<td>0.32</td>
</tr>
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<td>2-7</td>
<td>0.34</td>
</tr>
<tr>
<td>4-5</td>
<td>0.35</td>
</tr>
<tr>
<td>1-2</td>
<td>0.36</td>
</tr>
<tr>
<td>4-7</td>
<td>0.37</td>
</tr>
<tr>
<td>0-4</td>
<td>0.38</td>
</tr>
<tr>
<td>6-2</td>
<td>0.40</td>
</tr>
<tr>
<td>3-6</td>
<td>0.52</td>
</tr>
<tr>
<td>6-0</td>
<td>0.58</td>
</tr>
<tr>
<td>6-4</td>
<td>0.93</td>
</tr>
</tbody>
</table>
Kruskal’s algorithm: visualization
Kruskal’s algorithm: correctness proof

**Proposition.** [Kruskal 1956] Kruskal’s algorithm computes the MST.

**Pf.** [Case 1] Kruskal’s algorithm adds edge \( e = v-w \) to \( T \).
- Vertices \( v \) and \( w \) are in different connected components of \( T \).
- Cut = set of vertices connected to \( v \) in \( T \).
- By construction of cut, no edge crossing cut is in \( T \).
- No edge crossing cut has lower weight. Why?
- Cut property \( \Rightarrow \) edge \( e \) is in the MST.
Proposition. [Kruskal 1956] Kruskal’s algorithm computes the MST.

Pf. [Case 2] Kruskal’s algorithm discards edge $e = v-w$.
- From Case 1, all edges in $T$ are in the MST.
- The MST can’t contain a cycle. □
Kruskal’s algorithm: implementation challenge

Challenge. Would adding edge $v-w$ to tree $T$ create a cycle? If not, add it.

How difficult to implement?

A. $1$
B. $\log V$
C. $V$
D. $E + V$

Case 1: $v$ and $w$ in same component

Case 2: $v$ and $w$ in different components
Kruskal’s algorithm: implementation challenge

Challenge. Would adding edge $v$–$w$ to tree $T$ create a cycle? If not, add it.

Efficient solution. Use the union–find data structure.

- Maintain a set for each connected component in $T$.
- If $v$ and $w$ are in same set, then adding $v$–$w$ would create a cycle.
- To add $v$–$w$ to $T$, merge sets containing $v$ and $w$.

Case 2: adding $v$–$w$ creates a cycle

Case 1: add $v$–$w$ to $T$ and merge sets containing $v$ and $w$
public class KruskalMST
{
    private Queue<Edge> mst = new Queue<Edge>();

    public KruskalMST(EdgeWeightedGraph G)
    {
        DirectedEdge[] edges = G.edges();
        Arrays.sort(edges);
        UF uf = new UF(G.V());

        for (int i = 0; i < G.E(); i++)
        {
            Edge e = edges[i];
            int v = e.either(), w = e.other(v);
            if (uf.find(v) != uf.find(w))
            {
                uf.union(v, w);
                mst.enqueue(e);
            }
        }
    }

    public Iterable<Edge> edges()
    {
        return mst;
    }
}
Kruskal’s algorithm: running time

**Proposition.** Kruskal’s algorithm computes MST in time proportional to $E \log E$ (in the worst case).

**Pf.**

<table>
<thead>
<tr>
<th>operation</th>
<th>frequency</th>
<th>time per op</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sort</strong></td>
<td>1</td>
<td>$E \log E$</td>
</tr>
<tr>
<td><strong>Union</strong></td>
<td>$V - 1$</td>
<td>$\log V$ †</td>
</tr>
<tr>
<td><strong>Find</strong></td>
<td>$2E$</td>
<td>$\log V$ †</td>
</tr>
</tbody>
</table>

† using weighted quick union
Greed is good

Gordon Gecko (Michael Douglas) evangelizing the importance of greed (in algorithm design?)
Wall Street (1986)
Maximum Spanning Tree

Problem. Given an undirected graph $G$ with positive edge weights, find a spanning tree that maximizes the sum of the edge weights.

Running time. $E \log E$ (or better).
4.3 Minimum Spanning Trees

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- context
Prim’s algorithm demo

- Start with vertex 0 and greedily grow tree $T$.
- Add to $T$ the min weight edge with exactly one endpoint in $T$.
- Repeat until $V-1$ edges.

**Diagram:**

![Graph](https://via.placeholder.com/150)

*an edge-weighted graph*
Prim’s algorithm: visualization
Prim’s algorithm: proof of correctness

**Proposition.** [Jarník 1930, Dijkstra 1957, Prim 1959]
Prim’s algorithm computes the MST.

**Pf.** Let $e = \min$ weight edge with exactly one endpoint in $T$.
- Cut = set of vertices in $T$.
- No crossing edge is in $T$.
- No crossing edge has lower weight.
- Cut property $\Rightarrow$ edge $e$ is in the MST.  

*edge $e = 7-5$ added to tree*
Prim’s algorithm: implementation challenge

**Challenge.** Find the min weight edge with exactly one endpoint in $T$.

**How difficult to implement?**

A. 1
B. log $E$
C. $V$
D. $E$

1-7 is min weight edge with exactly one endpoint in $T$

<table>
<thead>
<tr>
<th>Edge</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-7</td>
<td>0.19</td>
</tr>
<tr>
<td>0-2</td>
<td>0.26</td>
</tr>
<tr>
<td>5-7</td>
<td>0.28</td>
</tr>
<tr>
<td>2-7</td>
<td>0.34</td>
</tr>
<tr>
<td>4-7</td>
<td>0.37</td>
</tr>
<tr>
<td>0-4</td>
<td>0.38</td>
</tr>
<tr>
<td>6-0</td>
<td>0.58</td>
</tr>
</tbody>
</table>
Challeng. Find the min weight edge with exactly one endpoint in $T$.

Lazy solution. Maintain a PQ of edges with (at least) one endpoint in $T$.

- Key = edge; priority = weight of edge.
- **Delete-Min** to determine next edge $e = v_w$ to add to $T$.
- If both endpoints $v$ and $w$ are marked (both in $T$), disregard.
- Otherwise, let $w$ be the unmarked vertex (not in $T$):
  - add $e$ to $T$ and mark $w$
  - add to PQ any edge incident to $w$ (assuming other endpoint not in $T$)
Prim’s algorithm: lazy implementation demo

- Start with vertex 0 and greedily grow tree $T$.
- Add to $T$ the min weight edge with exactly one endpoint in $T$.
- Repeat until $V - 1$ edges.

\[
\begin{array}{cccc}
0 & 7 & \text{0.16} \\
2 & 3 & \text{0.17} \\
1 & 7 & \text{0.19} \\
0 & 2 & \text{0.26} \\
5 & 7 & \text{0.28} \\
1 & 3 & \text{0.29} \\
1 & 5 & \text{0.32} \\
2 & 7 & \text{0.34} \\
4 & 5 & \text{0.35} \\
1 & 2 & \text{0.36} \\
4 & 7 & \text{0.37} \\
0 & 4 & \text{0.38} \\
6 & 2 & \text{0.40} \\
3 & 6 & \text{0.52} \\
6 & 0 & \text{0.58} \\
6 & 4 & \text{0.93} \\
\end{array}
\]

an edge-weighted graph
Prim’s algorithm: lazy implementation

```java
public class LazyPrimMST {
    private boolean[] marked;  // MST vertices
    private Queue<Edge> mst;   // MST edges
    private MinPQ<Edge> pq;    // PQ of edges

    public LazyPrimMST(WeightedGraph G) {
        pq = new MinPQ<Edge>();
        mst = new Queue<Edge>();
        marked = new boolean[G.V()];
        visit(G, 0);

        while (!pq.isEmpty() && mst.size() < G.V() - 1) {
            Edge e = pq.delMin();
            int v = e.either(), w = e.other(v);
            if (marked[v] && marked[w]) continue;
            mst.enqueue(e);
            if (!marked[v]) visit(G, v);
            if (!marked[w]) visit(G, w);
        }
    }
}
```

- assume G is connected
- repeatedly delete the min weight edge e = v–w from PQ
- ignore if both endpoints in T
- add edge e to tree
- add either v or w to tree
Prim’s algorithm: lazy implementation

```
private void visit(WeightedGraph G, int v) {
    marked[v] = true;
    for (Edge e : G.adj(v))
        if (!marked[e.other(v)])
            pq.insert(e);
}

public Iterable<Edge> mst() {
    return mst;
}
```

- add v to T
- for each edge e = v–w, add to PQ if w not already in T
Lazy Prim’s algorithm: running time

**Proposition.** Lazy Prim’s algorithm computes the MST in time proportional to $E \log E$ and extra space proportional to $E$ (in the worst case).

**Pf.**

<table>
<thead>
<tr>
<th>operation</th>
<th>frequency</th>
<th>binary heap</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DELETE-MIN</strong></td>
<td>$E$</td>
<td>$\log E$</td>
</tr>
<tr>
<td><strong>INSERT</strong></td>
<td>$E$</td>
<td>$\log E$</td>
</tr>
</tbody>
</table>
Prim’s algorithm: eager implementation

**Challenge.** Find min weight edge with exactly one endpoint in $T$.

**Observation.** For each vertex $v$, need only *lightest* edge connecting $v$ to $T$.
- MST includes at most one edge connecting $v$ to $T$. Why?
- If MST includes such an edge, it must take lightest such edge. Why?
Prim’s algorithm: eager implementation demo

- Start with vertex 0 and greedily grow tree $T$.
- Add to $T$ the min weight edge with exactly one endpoint in $T$.
- Repeat until $V - 1$ edges.

an edge-weighted graph

<table>
<thead>
<tr>
<th>Edge</th>
<th>Weight</th>
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</thead>
<tbody>
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<tr>
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<td>0.93</td>
</tr>
</tbody>
</table>
Prim’s algorithm: eager implementation demo

- Start with vertex 0 and greedily grow tree $T$.
- Add to $T$ the min weight edge with exactly one endpoint in $T$.
- Repeat until $V-1$ edges.

MST edges

\[
\begin{array}{ccccccc}
0-7 & 1-7 & 0-2 & 2-3 & 5-7 & 4-5 & 6-2 \\
\end{array}
\]
**Challenge.** Find min weight edge with exactly one endpoint in \( T \).

**Eager solution.** Maintain a PQ of vertices connected by an edge to \( T \), where priority of vertex \( v = \) weight of lightest edge connecting \( v \) to \( T \).
- Delete min vertex \( v \); add its associated edge \( e = v - w \) to \( T \).
- Update PQ by considering all edges \( e = v - x \) incident to \( v \)
  - ignore if \( x \) is already in \( T \)
  - add \( x \) to PQ if not already on it
  - decrease priority of \( x \) if \( v - x \) becomes lightest edge connecting \( x \) to \( T \)
Indexed priority queue

Associate an index between 0 and $n - 1$ with each key in a priority queue.

- Insert a key associated with a given index.
- Delete a minimum key and return associated index.
- **Decrease the key** associated with a given index.

```java
public class IndexMinPQ<Key extends Comparable<Key>> {
    IndexMinPQ(int n) {
        // create indexed PQ with indices 0, 1, ..., n – 1
    }
    void insert(int i, Key key) {
        // associate key with index i
    }
    int delMin() {
        // remove a minimal key and return its associated index
    }
    void decreaseKey(int i, Key key) {
        // decrease the key associated with index i
    }
    boolean contains(int i) {
        // is i an index on the priority queue?
    }
    boolean isEmpty() {
        // is the priority queue empty?
    }
    int size() {
        // number of keys in the priority queue
    }
}
```

For Prim’s algorithm, $n = V$ and index = vertex.
Indexed priority queue: implementation

**Binary heap implementation.** [see Section 2.4 of textbook]

- Start with same code as MinPQ.
- Maintain parallel arrays so that:
  - `keys[i]` is the priority of vertex `i`
  - `qp[i]` is the heap position of vertex `i`
  - `pq[i]` is the index of the key in heap position `i`
- Use `swim(qp[i])` to implement `decreaseKey(i, key)`.

```
<table>
<thead>
<tr>
<th>i</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>keys[i]</td>
<td>A</td>
<td>S</td>
<td>O</td>
<td>R</td>
<td>T</td>
<td>I</td>
<td>N</td>
<td>G</td>
<td>-</td>
</tr>
<tr>
<td>qp[i]</td>
<td>1</td>
<td>5</td>
<td>4</td>
<td>8</td>
<td>7</td>
<td>6</td>
<td>2</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>pq[i]</td>
<td>-</td>
<td>0</td>
<td>6</td>
<td>7</td>
<td>2</td>
<td>1</td>
<td>5</td>
<td>4</td>
<td>3</td>
</tr>
</tbody>
</table>
```

decrease key of vertex 2 to C

vertex 2 is at heap index 4
Prim’s algorithm: which priority queue?

Depends on PQ implementation: $V$ \textsc{insert}, $V$ \textsc{delete-min}, $\leq E$ \textsc{decrease-key}.

<table>
<thead>
<tr>
<th>PQ implementation</th>
<th>\textsc{insert}</th>
<th>\textsc{delete-min}</th>
<th>\textsc{decrease-key}</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td>unordered array</td>
<td>1</td>
<td>$V$</td>
<td>1</td>
<td>$V^2$</td>
</tr>
<tr>
<td>binary heap</td>
<td>$\log V$</td>
<td>$\log V$</td>
<td>$\log V$</td>
<td>$E \log V$</td>
</tr>
<tr>
<td>d-way heap</td>
<td>$\log_d V$</td>
<td>$d \log_d V$</td>
<td>$\log_d V$</td>
<td>$E \log_{E/V} V$</td>
</tr>
<tr>
<td>Fibonacci heap</td>
<td>$1^\dagger$</td>
<td>$\log V^\dagger$</td>
<td>$1^\dagger$</td>
<td>$E + V \log V$</td>
</tr>
</tbody>
</table>

$^\dagger$ amortized

Bottom line.

- Array implementation optimal for complete graphs.
- Binary heap much faster for sparse graphs.
- 4-way heap worth the trouble in performance-critical situations.
- Fibonacci heap best in theory, but not worth implementing.
4.3 **Minimum Spanning Trees**

- **introduction**
- **cut property**
- **edge-weighted graph API**
- **Kruskal's algorithm**
- **Prim's algorithm**
- **context**
Does a linear-time MST algorithm exist?

<table>
<thead>
<tr>
<th>year</th>
<th>worst case</th>
<th>discovered by</th>
</tr>
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<tr>
<td>1975</td>
<td>$E \log \log V$</td>
<td>Yao</td>
</tr>
<tr>
<td>1976</td>
<td>$E \log log V$</td>
<td>Cheriton–Tarjan</td>
</tr>
<tr>
<td>1984</td>
<td>$E \log^* V, E + V \log V$</td>
<td>Fredman–Tarjan</td>
</tr>
<tr>
<td>1986</td>
<td>$E \log (\log^* V)$</td>
<td>Gabow–Galil–Spencer–Tarjan</td>
</tr>
<tr>
<td>1997</td>
<td>$E \alpha(V) \log \alpha(V)$</td>
<td>Chazelle</td>
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<tr>
<td>2000</td>
<td>$E \alpha(V)$</td>
<td>Chazelle</td>
</tr>
<tr>
<td>2002</td>
<td>optimal</td>
<td>Pettie–Ramachandran</td>
</tr>
<tr>
<td>20xx</td>
<td>$E$</td>
<td>???</td>
</tr>
</tbody>
</table>

Deterministic compare-based MST algorithms

Remark. Linear-time randomized MST algorithm (Karger–Klein–Tarjan).
Euclidean MST

Given $n$ points in the plane, find MST connecting them, where the distances between point pairs are their Euclidean distances.

**Brute force.** Compute $\sim n^2/2$ distances and run Prim’s algorithm.  
**Ingenuity.** Exploit geometry; $n \log n$ using Delaunay triangulation.
**Minimum Bottleneck Spanning Tree**

**Problem.** Given an edge-weighted graph $G$, find a spanning tree that minimizes the maximum weight of its edges.

**Running time.** $E \log E$ (or better).

Note: not necessarily a MST

minimum bottleneck spanning tree $T$ (bottleneck = 9)